The development, theory and use of nickel-cadmium batteries

by P. N. BUTTERFIELD, BTech, PGDip, G4AAQ†

OVER the past five years, nickel-cadmium (nicad) batteries have become of ever-increasing importance to the amateur, especially with the increase in commercially available portable equipment. With this in mind, the author felt an article outlining the history and development of the nickel-cadmium battery, its theory of operation, and its performance and uses, would be of interest to the amateur. It may also clear up one or two misconceptions about nickel-cadmium batteries which have crept into conversations on the air.

History and development

The basic development of alkaline cells dates from 1881 when Lalande and Chaperon patented a cell which used a copper-oxide positive electrode and a zinc negative electrode in a potassium or sodium hydroxide electrolyte. Much work was done on this system, and in 1889 Thomas Edison patented a modified version of the Lalande-Chaperon cell. He later experimented with cadmium as a substitute for the zinc electrode but then turned his attention to nickel oxide and iron as electrode materials.

In Sweden, around the same period, Waldemar Jungner was working on alkaline electrolytes, experimenting with many combinations of metals and metal compounds. One of the major difficulties with the development of alkaline cells was that the electrolyte appeared to attack most metals by oxidation of the anode. Jungner undertook an investigation to find a metal which was not affected in this way: he came up with nickel and made this the support for active materials in his future experiments.

Jungner also carried out successful experiments on silver-cadmium cells, but the materials turned out to be either too expensive or too rare for exploiting on a large production basis. However, in 1901 Jungner patented a nickel-cadmium cell system.

The independent work done by Edison and Jungner formed the basis from which the successful manufacture of nickel-cadmium batteries began. These batteries were made by a similar process to the already common Planté lead-acid batteries, and the main application was as replacements for such batteries.

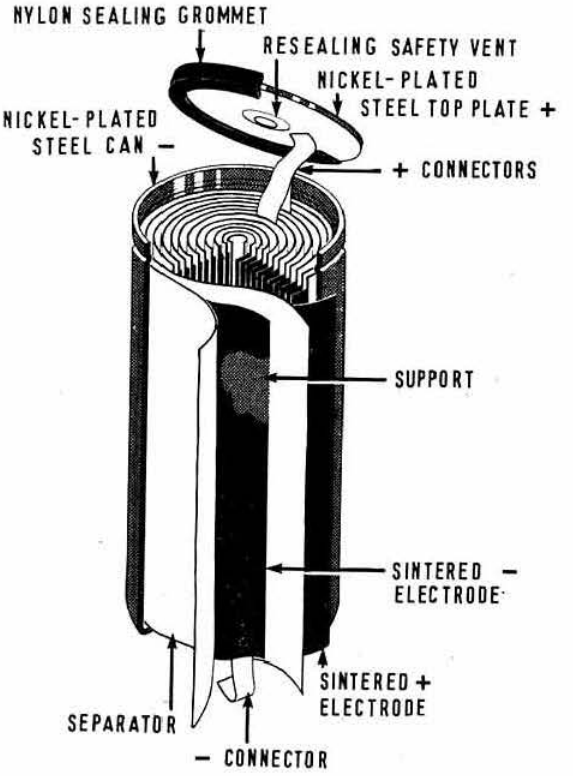

Fig 1. Exploded view of construction of typical nickel-cadmium cell

The next major step was made in the 'thirties in Germany, where the electrodes were developed, with the active materials deposited in the pores of sintered* nickel supports. Little use was made of this knowledge until the second world war, when sintered cells were manufactured in Germany and used in aircraft and rockets. These batteries had both mechanical and electrical shortcomings and it was not until after the war that these were resolved and the manufacture of sintered nickel-cadmium batteries was begun in several countries.

Development of a sealed system was considered by Edison in 1912. No practical system was evolved, however, until the early 'fifties, when intense research into nickel-cadmium batteries led to the discovery of the principle of oxygen re-combination. With the advent of suitable separator materials the sealed cell system was developed, and this resulted in a new era of nickel-cadmium technology and the manufacture and use of small, completely sealed rechargeable batteries.

Continued developments in the search for smaller, higher performance, nickel-cadmium batteries have resulted in cells in which construction allows any oxygen

† 33 Grime Lane, Sharlston Common, Nr Wakefield, West Yorks.

*Sintering is the process which brings about the agglomeration of particles of a metal (or other substance) by heating, usually under pressure, to just below the melting point of the substance, or in the case of a mixture, to the melting point of the lowest melting constituent.

produced during charging to be recycled so that the cell may be sealed. This means there is no loss of electrolyte nor any significant build-up of gas pressure under normal use.

The most effective construction has been proved to be one where the active materials are chemically formed within the pores of the sintered nickel plates, and in which the cell is assembled with electrodes of different capacities and an accurately determined amount of electrolyte.

Nickel-cadmium cells are produced in both cylindrical and button type construction. Electrically and chemically both these types are identical and only differ in the physical construction. For amateur purposes the cylindrical sintered plate cell is the one most commonly used, and the remainder of this article is written with emphasis on this type of cell. The button type cell has many similarities but is generally designed for smaller capacities and lower current drains. If the reader wishes to use the button cells, he is advised to get the manufacturer's instructions for their use rather than directly apply the information given later in this article, which is applicable only to the sintered plate cell and, if used on button cells, could lead to reduced cell life due to overcharging or over-discharging.

Theory of operation

The sealed nickel-cadmium cell has a similar chemical reaction to the open nickel-cadmium cell. It is designed to be maintenance-free and under normal conditions it will not release gas, whereas an open cell is designed to release gases when necessary and may require topping up or a complete electrolyte change.

The elements of construction of the cylindrical sintered cell are shown in Fig 1. The key to the success of the system is the microporous pure nickel matrix which is formed about the perforated nickel or nickel-plated mesh making up the electrode support.

The interstices of this material are impregnated with the active electrode materials following high vacuum treatment to ensure that a high degree of utilization of space is achieved. Connections to the electrode packs are in all cases pure nickel strips welded to the plated steel outer casing. The electrode separators are formed from non-woven polyamide materials specially selected for long term chemical and physical stability.

Cell assembly is carried out under rigidly-controlled conditions, and the final hermetic closure is achieved by forming a pressure seal between the top of the can and a creep-resistant insulating nylon grommet or top plate. In addition, all the cylindrical type cells are fitted with a resealable safety vent, enabling the cell to release a little gas under conditions of extreme abuse, and then to reseal and function normally thereafter. Most nickel-cadmium cylindrical cells are designed to vent at between 10 and 20 atmospheres; however, it has been noted that several types of cells of oriental origin vent at a much lower level than 10 atmospheres, which in the long term leads to reduced life. Hence, with cells of this nature it is imperative that they are treated carefully and not abused.

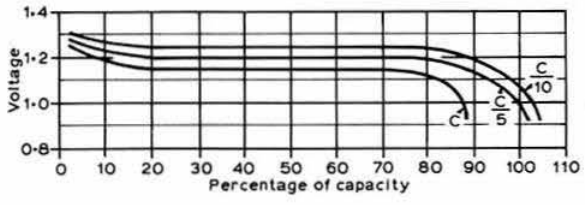

Fig 2. Typical capacity variation with discharge rate

The electro-chemical theory underlying this construction can now be considered. An approximation of the overall charge and discharge reactions of any nickel-cadmium cell may be represented by the following reversible reaction:

$$\underset{\text{Positive electrode}}{2Ni(OH)_2} + \underset{\text{negative electrode}}{Cd(OH)_2} \rightleftharpoons \underset{\text{positive electrode}}{2NiO(OH)} + \underset{\text{negative electrode}}{Cd + 2H_2O}$$

DISCHARGED STATE — CHARGED STATE

More detailed consideration of the individual electrode reactions during charge shows that the main negative electrode reaction, consisting of the reduction of cadmium hydroxide by absorbing electrons—$Cd(OH)_2 + 2e^- \longrightarrow Cd + 2OH^-$, is accompanied by a side reaction—$2H_2O + 2e^- \longrightarrow 2OH^- + H_2$.

However, the hydrogen evolution potential is not reached during charging at moderate rates and thus the hydrogen producing side reaction does not occur to any measurable extent.

Similarly, the positive electrode reaction—$2Ni(OH)_2 + 2OH^- \longrightarrow 2NiO(OH) + 2H_2O + 2e^-$, is accompanied by a side reaction—$4OH^- \longrightarrow 2H_2O + O_2 + 4e$.

By constructing the cell as shown earlier, the migration of oxygen evolved at the positive electrode is promoted to the vicinity of the negative electrode. Here, the oxygen is reduced on contact with the negative electrode by the reverse of the above reaction which absorbs electrons. Thus it can be seen that the electrons are not available for the reduction of the cadmium hydroxide. This no longer takes place and, therefore, the hydrogen evolution potential is not reached.

This state of affairs continues to exist as long as the rate of oxygen evolution at the positive electrode is no higher than the rate of its consumption at the negative electrode. Most cells have an additional built-in protection against overcharge which takes the form of a surplus amount of cadmium hydroxide incorporated into the structure of the negative plate. This surplus mass is called "charge reserve", and it ensures that the negative electrode is only partially charged when the positive electrode is fully charged.

Two practical points emerge from the above considerations. First, when the cell is fully charged all the current being passed will be used in the production of oxygen and its subsequent recombination, and the greater the current the more oxygen will be produced. If too high a charging current is used, more oxygen will be produced than can be recombined, gas pressure will build up and the safety vent will release oxygen from the sealed cell.

Second, it should be noted that the oxygen recombination reaction is exothermic and will cause the cell temperature to rise. (The resultant temperature rise is not caused by the cell's internal resistance.) Too great a temperature rise may damage the cell. It is therefore

necessary to limit charging current if there is any possibility of the cell being overcharged.

It will be noted that no mention of the electrolyte, potassium hydroxide (KOH), has been made and it does not appear in any of the formulas. However, water is produced when charging and is taken up when discharging. The purpose of the electrolyte is to reduce the effect of the water on the operation of the cell.

Performance and use

Capacity. The capacity of a battery is the total amount of electrical energy (expressed in ampere-hours) which can be obtained from it when fully charged. The available capacity is normally dependent on the rate of discharge, the temperature, the nominal and final discharge voltage and its recent history in terms of charge and discharge cycles.

The standard capacity of nickel-cadmium batteries (C) is the capacity which will be obtained when fully charged batteries are discharged at such a rate as will bring them to an end point of 1V in five hours. This end point is chosen because, at that voltage, the cell is effectively exhausted. This rate of discharge is known as the five-hour rate and is usually expressed as C/5.** Similarly, C/2 indicates a two-hour discharge rate and 2C indicates a complete discharge in 30min.

As mentioned earlier, the capacity varies with the discharge rate. Slightly higher capacities will be obtained if the discharge rate is reduced below C/5 (say C/10) and reduced capacities will result if the discharge rate is increased above C/5 (say C). This variation is shown in Fig 2.

For example, if a standard "AA" size, 450mAh battery at 25°C is discharged at a rate of 90mA, the full capacity of 450mAh will be obtained. If, however, it is discharged at 450mA, only 86 per cent of its full capacity, 390mAh will be obtained.

The capacity is also a function of temperature, and this is shown in Fig 3. If the cell is operated at any temperature other than 25°C, its capacity must be up-rated or de-rated. Using the previous example of a battery discharging at 450mA, if it was doing so at 0°C, only 61 per cent (0·71 × 0·86 × 100) of its full capacity, 275mAh, would be obtained.

**In certain literature, C may be denoted as I.

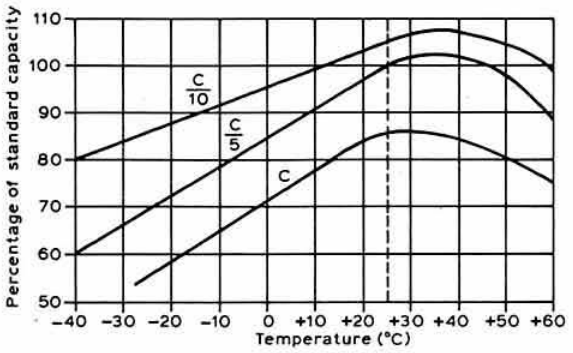

Fig 3. Typical capacity variation with temperature

Temperature. Nickel-cadmium cells will operate over a wide temperature range (−40°C to +60°C) and in a variety of unusual environments, eg in gravity free conditions or in a vacuum. The capacity of these batteries varies with temperature, as mentioned earlier, being greatest at about 30–40°C (Fig 3). At temperatures below 0°C, the battery's internal resistance increases and this can greatly affect the voltage characteristic at high discharge rates. Also, at low temperature, the battery's ability to recombine oxygen during overcharge is inhibited and, therefore, under normal circumstances, charging should not be attempted at low temperatures.

Nickel-cadmium batteries have a negative temperature coefficient of approximately 4mV/°C per battery. When selecting batteries for low temperature operation, both their reduced capacity and changed voltage characteristic should be taken into consideration.

Efficiency. Nickel-cadmium batteries with sintered electrodes have an ampere-hour efficiency of approximately 84 per cent. For this reason they have a charging factor of 1·2. Therefore, to completely charge a fully discharged battery, 20 per cent more energy must be put back into the battery than has been withdrawn.

The watt/hour efficiency is the ratio of the discharged energy to the necessary energy needed to charge a battery fully. Comparing the mean discharge voltage with the mean charge voltage gives approximately 73 per cent for a battery with sintered electrodes when discharged at the C/10 rate.

Storage. Sealed nickel-cadmium batteries can be stored indefinitely; ideally in a clean, dry atmosphere, in a discharged state—unlike lead-acid batteries which will sulphate if stored in a discharged state. Nickel-cadmium batteries can be stored in any state of charge without significant loss of life.

Maintenance charging is not required. However, after prolonged storage, up to three cycles of charge and discharge may be required to achieve the battery's rated capacity. It is recommended that the first charge in these circumstances should be for 24 hours at the C/10 rate.

During operation and storage it is possible that crystals may form in the area of the sealing gasket between the positive nickel-plated steel top plate and the negative nickel-plated steel can. These crystals form because of minute pores in the sealing ring which allow the electrolyte, potassium hydroxide, to combine with carbon dioxide from the atmosphere forming potassium carbonate. The crystals have no detrimental effect on the electrical properties or life expectancy of the battery and may be removed with a dry cloth. A smear of silicone grease round the edge of the sealing gasket will inhibit further growth.

Charge retention. Sealed nickel-cadmium batteries have a moderate self-discharge characteristic at normal temperatures. Fig 4 illustrates this and, as can be seen, the self-discharge is a function of the battery temperature. The loss is not harmful to the battery and the energy may be readily restored at any time by recharging.

Charging. An advantage of nickel-cadmium batteries is that they may be charged satisfactorily with very simple circuitry, but in all cases the current should be approximately constant or limited to a known safe value. Under

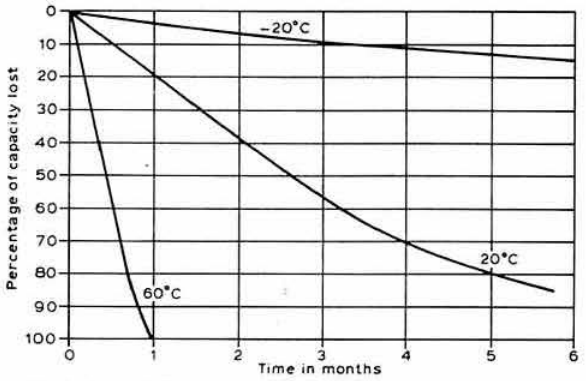

Fig 4. Typical charge retention characteristics with time

no circumstances should a constant potential charging system (such as a car battery) be used, since the very low internal resistance (approximately 20mΩ) of the nickel-cadmium battery may lead to very high currents being drawn and to the battery overheating. Also, since it is necessary to inhibit the evolution of gas within a sealed cell, the voltage rise caused by a cell gassing cannot be used to reduce the charge current to a safe trickle charge level. Many methods of determining the state of charge of a sealed nickel-cadmium battery have been tried but, due to the nature of the charge/discharge characteristics, no commercially viable system has yet been developed to give a sufficiently accurate indicator.

Discharged batteries (ie batteries below 1V) can be brought to the fully charged state after 12 to 14 hours if charged at the C/10 rate. If batteries are discharged much below 1V (ie overdischarged), reverse polarity may take place. In these circumstances it is recommended that an extended charge of 24 hours at the C/10 rate be given to ensure that the battery is charged to the correct level. Overcharge at rates in excess of C/10 should be avoided; however, 100 hours at the C/10 rate will have no detrimental effect.

There are many applications where it is necessary to maintain batteries in a fully charged condition at all times, eg emergency power supplies. In such cases, where deliberate indefinite overcharging has been planned for, the charge rate necessary to keep the battery fully charged is approximately the C/30 rate. This allows for normal self-discharge but the rate should be increased to C/10 if there is any major withdrawal of charge.

If the exact state of charge of a battery is known—and this is usually only when it is completely discharged—it is possible to charge very rapidly (at $10 \times C/10$ rate to approximately 80 per cent capacity). However, this must only be done under very carefully controlled conditions, and excessive temperatures must be avoided if the

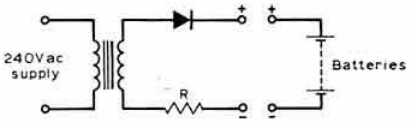

Fig 5. Simple mains charging circuit

expected life of the battery is to be attained. Any reduction in life may not become apparent until the battery has been in service for periods in excess of one year. It is not recommended that the reader attempts fast charging of nickel-cadmium batteries.

In applications where batteries are operated in a purely cyclic mode (ie charge/discharge cycle) at the C/10 rate, sintered electrode batteries should give 500 cycles to approximately 80 per cent capacity. Partial discharging will increase the number of cycles achieved quite significantly. Similarly, discharging at high rates, above C/5, will reduce the expected life of the battery.

Charging circuits

The coulombs stored by a battery during charge, or delivered during discharge, are a function only of mean current for short term cyclic variations. Consequently, it is an accepted practice to use unsmoothed rectified supplies, resulting in the battery current pulsing at harmonics of the supply frequency.

One of the simplest forms of charger circuit is shown in Fig 5 and consists of a transformer, half-wave rectifier and current limiting resistor. As a rule, the output voltage of the transformer should be about twice the on-charge battery voltage, which is about 1·45V per battery. The value of R is chosen to limit the current to the desired value. For greater efficiency it is possible to use full-wave rectification.

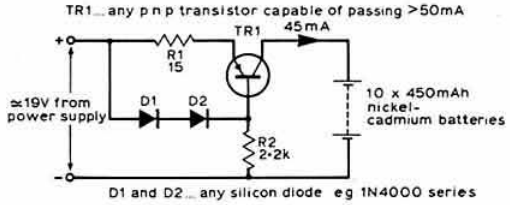

Fig 6. Constant current regulator

Such chargers are typical of the ones normally supplied with commercial portable equipment. However, one of the major disadvantages of such chargers is the absence of control over voltage variations and, in turn, the charging current. The problem of varying current can be overcome by using a constant current regulator. A suitable constant current regulator for charging nickel-cadmium batteries is shown in Fig 6, with component values to give a constant charge current of 45mA for a wide variation of input voltages. If the transistor TR1 is rated at 1W dissipation, the circuit will withstand a short-circuited output.

This still leaves two major problems. First, the need for a transformer which is a relatively bulky and costly item, and second, the fact that the charger cannot be used while the equipment is in the car. The difficulty is that the car battery voltage ($13V \pm 2V$) is insufficient to drive a constant current regulator under all conditions.

Many amateurs have a 12V source in their shack, and most have one in their car! The simple and inexpensive circuit shown in Fig 7 was developed for a local radio club project by G3WUI. It eliminates the need for a transformer, providing that a 12V supply is available. It provides

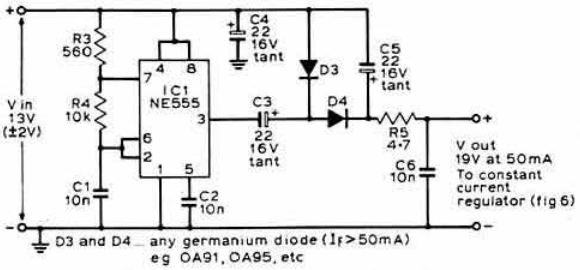

Fig 7. Simple 13V battery-source charging circuit

Table 1. Results of dc–dc converter charging circuit

V_{in} (V)	I_{in} (mA)	I_{out} (mA) without const current reg	I_{out} (mA) with const current reg
11	130	29	41
12	140	39	42
13	148	47	43
14	153	56	44
15	160	65	45

V_{in} = 13·0V ±2V (±15%)
I_{out} (without regulator) = 47mA ±18mA (±38%)
I_{out} (with regulator) = 43mA ± 2mA (±4·65%)

sufficient voltage and current to enable ten 450mAh nickel-cadmium batteries to be charged at the C/10 rate.

The heart of the system is a low current dc-dc converter using a Signetics NE555 integrated circuit. It operates as a multivibrator, at a frequency of about 8kHz, with a 1:1 mark-space ratio. A voltage doubler provides 19V at 50mA, and the overall efficiency is about 70 per cent. The current regulator is the same as that shown in Fig 6, and the results obtained with this configuration are shown in Table 1. The output current does not vary more than ±4·65 per cent for an input variation of ±15 per cent, which makes it suitable for use in a car whether mobile or stationary. The unit can be built on a piece of Veroboard about 1·2in square and, with some simple switching arrangement, could be mounted internally or externally, allowing the equipment to be used while mobile and to be charging the internal nickel-cadmium batteries at the same time. The advantages of such a system are obvious, especially where it is necessary to have the equipment operational at all times in fixed, mobile and portable conditions.

Conclusion

The characteristics of these small, compact power sources are such that the author expects they will find rapidly increasing applications in the field of amateur radio in the future. This article has briefly outlined the history, electrochemical and physical construction and typical operating characteristics of cylindrical sintered electrode nickel-cadmium batteries, together with some simple charging circuits. It is hoped that the reader now has a more optimistic view of nickel-cadmium batteries, and the author will be pleased to supply further information and advice to anyone requiring it. □

oscar news

Oscar 8 continues in a stable orbit, and daily reference figures can be obtained from GB2RS or one of the Oscar nets on Sundays. Severe fading has been noted on Mode A and this could be due to Faraday rotation or ionospheric effects during periods of high solar activity.

	OSCAR 7	OSCAR 8
145–29MHz transponder	Uplink: 145·85–145·95MHz Downlink: 29·4–29·5MHz (Mode A)	Uplink: 145·85–145·95MHz Downlink: 29·4–29·5MHz (Mode A)
432–145MHz transponder	Uplink: 432·125–432·175MHz Downlink: 145·975–145·925MHz (Mode B)	—
145–435MHz transponder	—	Uplink: 145·900–146·000MHz Downlink: 435·1–435·2MHz (Mode J)
Beacons	435·10MHz (Mode A) 145·972MHz (Mode B) 29·502MHz (Mode A)	435·095 (Mode J) 29·402 (Mode A)

A calendar of Oscar 8 orbits, similar to the Oscar 7 calendar produced by W6PAJ, will be available at the beginning of June from AMSAT-UK. The cost to AMSAT-UK members will be £1.40, and G3AAJ will be the source of supply.

Users should note that neither Oscars 7 nor 8 are available for use on Wednesdays, which are reserved for AMSAT-designated experimental use.

The table shows the main characteristics of the two spacecraft now in orbit. Certain of the Oscar 8 figures may change slightly during the ensuing month.

	OSCAR 7	OSCAR 8
Period	114·944834min	103·23162min
Longitude increment	28·736208°W per orbit	25·80868°W per orbit
Inclination	101·7010°	98·992°
Perigee	1,450km	898·259km
Apogee	1,461km	910·37km
Eccentricity	0·0010218	0·00070
NASA object No	74 89 B	78 026 B
Schedule	Not to be used on Wednesdays. Otherwise mode according to battery state.	Not to be used on Wednesdays. Usually—Mode A, Monday to Friday; Mode J, Saturday and Sunday.